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Solar Power for Cathodic Protection of Bridge Decks

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ABSTRACT

Cathodic protection has been successfully applied in Ontario for almost a decade, to control the corrosion of rebars in reinforced concrete bridge decks. This paper discusses a means of converting sunlight to direct current electricity for cathodic protection. The method discussed is effective in protecting from corrosion remote bridges where commercial power is unavailable, too costly, or unreliable. Descriptions of the principle components of a solar unit and their main features are also included.

1/ INTRODUCTION

Many concrete bridge decks in North America are showing signs of distress, largely due to corrosion of the reinforcing steel (rebars) in the bridge deck. Corrosion of these rebars is initiated by the penetration of de-icing salts, which lower the pH of the concrete to a level at which steel is no longer passive and corrosion starts [1].

Cathodic protection is a system by which an electric potential is applied to the rebars so that they are made cathodic with respect to the surrounding concrete. This cathodic (or negative) potential prevents the ferrous ions from leaving the rebar and thus shuts off the corrosive reaction [2].

There are about 30 bridges in Ontario which have been cathodically protected. During the next year, several more bridges will be protected in this manner. All of these bridges are close to power lines from which electrical power may be obtained. For bridges remote from power lines, some other energy source must be sought if cathodic protection is to be applied to protect these bridge decks from corrosion. Two relatively maintenance-free sources of power are available for such situations -- solar power and wind power. Of these two, solar power appears to offer the best chance of success. The idea of using energy from the sun's abundant source has been a dream of man for centuries. Today, it is a reality through the photovoltaic effect, in which light energy is converted into direct current electricity without moving parts.

In order to determine if solar power will provide a constant source of sufficient power for cathodic protection, a trial installation was necessary. Such an installation was made in the Toronto area on one of the bridges already under cathodic protection from another power source.

Advantages of a Solar Power System

1/ A solar system is virtually maintenance free with little or no operating cost. The only required maintenance is the addition of water to the battery once a year. The tilt of the panel and the natural

cleansing action of the wind and rain tend to prevent an accumulation of dirt, dust, or snow.

2/ Solar arrays have a high potential for a reliable and long operational life. Solar panel life is estimated at 20 years; batteries, depending upon the type, will last 10 years or more. The solar generating system can be moved to another site, preserving the entire investment over its long, useful life. Panels can be replaced quickly, or added to the system should ground bed power requirements increase.

3/ Solar power produces no adverse environmental effects. Also, one of the features of a solar cell power plant is that the correct size can be chosen, rather than one that is larger than required and thus more expensive.

4/ They are inherently safe because no high voltages are generated, and are relatively easy to install.

5/ Restrictive electrical codes that exist in some areas do not apply to solar systems.

6/ If a solar panel surface should eventually become too inefficient, it could be resurfaced for a small fraction of the new module cost.

7/ At the present time, the Ministry pays a small yearly rate to Hydro for the use of electricity to power the rectifier unit for cathodic protection. This charge could be totally eliminated if solar cells were used.

8/ When pole lines are 1 km or more distant from the conventional electric power, solar energy sources are price competitive, especially when lower power requirements are necessary (less than 25 W).

2/ SYSTEM DESIGN

The Duffin's Creek bridge on Highway 7 near Toronto was ideal for experimental work and thus was chosen for the first solar power experimental installation. This bridge already had cathodic protection applied, so an existing anode bed was present which simplified the system design. The existing total circuit resistance and the total power required for cathodic protection were known. (This bridge and the cathodic protection are described in Reference 3.)

Load requirements for this bridge were 24 Ah (ampere hours) per day. Allowing a 25% design factor brought the required power to 30 Ah of current. Thus, during any 24-hour period, the system must deliver 30 Ah of current. During winter months, the sun only gives a peak light daily average of 2.5 h. As the solar array must replenish the power depleted by a 24-hour load in 2.5 h of peak sun, a large enough array was selected to accomplish this in the limited time available.

The array was rated at 60 W peak (12 A and 5 V). An "equivalent sun hour" is one hour of sunlight at its typical maximum intensity of 100 mW/cm^2. Therefore, 12 h of sunlight with an average intensity of 40 mW/cm^2 equals 0.40 x 12 or 4.8 equivalent sun hours. Assuming 2.5 h of peak sun hours per day, the system multiplier was 9.6. This meant that a 1 A cathodic protection system required 9.6 A of solar array. Allowing a design factor of 25% meant that a 12 A module was required.

The solar panel was located facing due south, and its angle of operation adjusted to 60° from the horizontal to maximize sunlight conditions during the winter months [9]. The cleansing action of the wind and rain prevented snow buildup and helped to keep the solar panel's surface clean. The solar panel was mounted on the MTC electric service wooden pole adjacent to the structure. The top of the panel was 6 m (20 ft) above the roadway level.

Battery selection was accomplished by taking the current load per day (30 Ah) and multiplying it by the number of days that the sun did not shine. Between 10 and 30 days were normally allowed as no-sun

conditions. Assuming 20 days of no-sun conditions as the safety factor, the battery had a capacity of (30 x 20) 600 Ah. Finally, it was necessary to increase the battery capacity to allow for low temperature protection. Investigators claimed that in latitudes of 40° to 50°, the daily load in ampere hours per day should be multiplied by a factor of 25 [8]. (If appropriate insulation is used, however, this factor may be reduced to 7.)

Thus, the battery capacity was increased by 30 x 25 or 750 Ah. This increased the battery capacity to 600 + 750 or 1350 Ah, containing a large safety factor. Since lead-acid batteries were relatively inexpensive compared to the solar panel, this safety factor was justified. A lead-calcium storage battery rated at 1055 Ah was selected for the system Two of these batteries connected in series gave the required capacity to run the cathodic protection in the bridge effectively.

The solar panels were environmentally sealed and packaged to protect them from rocks, hail, water, snow and ice, blowing sand, and birds. The individual solar modules were mounted in an aluminum array frame to provide position, correct angle and rigidity to the system. Connections between assemblies were made of convenient weather-resistant interconnections [7].

The batteries were protected from freezing by being buried below ground level and insulated. The battery enclosure was fabricated from an 810 mm diameter galvanized conduit 910 mm deep. A plate was welded to the bottom and a lid was made for the top of the conduit. This enclosure was buried to about 30 mm below the bottom lip of the lid. This allowed easy access to the batteries and to all internal components for maintenance [7].

The voltage (IR) drop in the wire from module to battery was kept to a minimum (below 0.3 V) [8]. The cable was large enough to carry a relatively high current (12 A) without exceeding this voltage loss. Since there was a run of 9 m (30 ft), a #6 wire was used. A #6 wire had a voltage drop of 0.14 V over a run of 9 m (30 ft). Since the solar panel's output was approximately 5.5 V and there was a 0.4 V drop in the diode and a 0.14 V drop in the wire, there remained almost 5 V to charge up the battery (rated at 4.2 V).

3/ INSTALLATION AND RESULTS OF SOLAR SYSTEM

During October 1981, work was initiated on the installation of the solar panel at Duffin's Creek. The solar panel (Solarex Model No. PL100) was mounted on the MTC wooden pole adjacent to the bridge structure. A wire mesh screen was placed as a border around the panel. This was necessary to prevent rocks or other thrown objects from contacting the rubber backing of the panel.

After the appropriate electrical wiring connections were made, the solar regulator was adjusted to allow the batteries to be charged up to 4.8 V (manufacturer's recommendation). The bridge deck was energized and cathodic protection applied. No problems were encountered during the installation or start-up procedures.

During the winter, however, it was observed that the control monitor unit would oscillate its output potential to the bridge whenever the bridge reached its upper potential limit. Although this oscillation was not detrimental to the cathodic protection, it was felt that it should be remedied. The control monitor circuit was redesigned and the oscillation was removed.

After six months of winter operation, the solar panel frame was examined and found to be sturdy and still angled at 60° from with the horizontal, indicating no slippage in the tilt angle. Prior to winter the batteries were insulated by means of a fibreglass material, which worked well. A maximum-minimum thermometer placed directly over the batteries registered a minimum temperature of -7°C. During the past winter there were several days and nights when the ambient temperature dropped to less than -25°C.

The system of burying and insulating the batteries performed better than expected. In future, it will not be necessary to include a large safety factor when purchasing batteries. Instead of increasing the daily ampere hour requirement by a factor of 25, as mentioned previously in the design section, a much smaller factor may be utilized. (This factor would have been as low as 7 at Duffin's Creek.) This will reduce some of the initial investment.

As previously mentioned, the battery enclosure was buried next to the wooden pole, approximately 6 m (20 ft) below the solar panel. In future, it is recommended that, if possible, the enclosure be buried beneath the bridge. This will afford the batteries a more controlled environment.

After approximately six months of operation, the batteries required only a small amount of distilled water to bring the electrolyte back to the original level.

The data listed in Table 1 were recorded at Duffin's Creek during different periods of the year, and illustrate power requirements for the bridge and solar array output under different weather conditions. As the ambient temperature decreases, it causes the bridge deck resistance to increase. As this resistance increases, the current required to achieve cathodic protection is reduced. This explains the low current readings observed in January and February. Also, if moisture penetrates the bridge deck, as after a shower, the deck resistance decreases -- causing an increase in the required current. This explains the "relatively" high current draw during the months of June and July. These two months received above average rainfall.

The maximum current output recorded for the solar panel was about 8 A.

4/ SYSTEM COSTS

At the present time, solar power cannot economically compete with at-the-site commercial grid power on a one-for-one basis. Even if grid power is as close as 1 km to a site, the costs of power extensions make a solar system highly competitive. In addition, with a solar power system there would not be the continuing utility costs of using grid power [4].

The total cost of the solar installation has two major components:

	cost	cost/peak watt
1/ solar panel array & accessories	$1864	$31
2/ lead-calcium battery	$ 802	$13
Total	$2666	$44

The cost of the solar array includes the solar panel; the pole mounting kit with adjustable leg assemblies; and a battery regulator to prevent the solar panel overcharging the batteries and to prevent the batteries from discharging through the solar panel during the night or on cloudy days. At present, the initial investment for a solar power generator is in the vicinity of $2700. The cost per peak watt for the system is around $44. This does not include the branch transfer charges required for at-the-site installation.

Over the past decade the cost per peak watt for a solar generator has decreased considerably. With improving technology it is expected that this cost will continue to be reduced.

5/ RECOMMENDATIONS AND CONCLUSIONS

Cathodic protection powered by solar energy has been in operation at Duffin's Creek since October 1981. Since the initial installation, no major problems have been encountered and there has been a continuous flow of power available to charge up the bridge for cathodic protection. The solar installation for cathodic protection is performing well, and the experience gained at this bridge may be used to extend the application of cathodic protection to remote locations previously left unprotected.

APPENDIX A/ SOLAR PANEL AND COMPONENTS

Sunlight (electromagnetic energy) can be converted directly into electricity by a process known as photovoltaic conversion, and a semiconductor device which utilizes this photovoltaic property is known as a solar cell. The basic elements required in a solar power supply are shown in the simplified diagram, Figure 1. They include: the photovoltaic energy converter (called "the solar panel"); blocking diode; storage battery; charging regulator; and load monitor/controller.

Solar Cell

The heart of this system is a silicon solar cell, Figure 2 [4]. Wafers for solar cells are made of single-crystal, high-purity silicon. Currently, silicon is the second most abundant element on earth. Since pure silicon is a poor conductor, silicon is "doped" by the addition of very small amounts of "impurities" which make the silicon more conductive. If doped with phosphorus, the wafer will conduct negative (n) charges called electrons. This occurs because the phosphorus atoms give up electrons to the silicon to form an area where there exists an excess of negative charges. If boron is used, the boron atoms absorb electrons from the silicon, leaving 'holes' (missing electrons) which behave like excess positive charges (p) and forming p-type silicon.

A p-n junction can be formed by allowing boron to diffuse into the surface of an n-type single-crystal wafer at high temperatures. The p-n junction formed between the n-type silicon wafer and the p-type surface layer provides the electric fields which give rise to the diode characteristics as well as the photovoltaic effect. Sunlight is absorbed in the silicon by generating both excess holes and electrons. If this occurs near the p-n junction, the electric fields present there will act to separate the holes from the electrons, causing the holes to build up in the p-type material and the electrons in the n-type material.

By connecting wires to the n- and p-type regions, these excess charges generated by the light and separated by the junction can be made to flow through an external circuit to provide power to an external load. These solar cells are then interconnected in series and parallel configurations

to produce the desired voltage and current for each solar application [8].

The spectral response of a typical solar cell is shown in Figure 3 [4]. The peak response is 600 to 1000 nm (nanometres) in wavelength, which is partly in the visible light spectrum and into the infrared area. Therefore, they produce energy whenever there is light, even on heavily overcast days [4].

Each typical cell is capable of delivering a maximum operating voltage of 0.45 V which is independent of the cell's surface area. This voltage will remain 0.45 V at all solar intensities, cloudy or clear days (Figure 4) [4]. The current output is directly proportional to the surface area, efficiency and to the light intensity that the solar cell sees. Full sun intensity is equivalent to an illumination level of 100 mW/cm^2. The cell's efficiency is a ratio of the cell's power output to the sun's power input, usually between 10% and 15%. Making a good connection to such a thin layer (n-layer, previously mentioned) requires a precision process The situation is further complicated by the fact that the metallic material, used to make the connection, will block some of the light that would otherwise penetrate to the junction. This blocking will reduce the efficiency of the cell. Another factor that can reduce the efficiency of a solar cell is reflection from its surface. Practical cells have a very thin anti-reflection coating similar to that used on photographic lenses. This explains, in part, why the maximum efficiency of a solar cell is approximately 25%.

Temperature also affects solar cell output. Using a temperature of 25°C ± 3°C as a standard, the output voltage of each cell varies inversely with temperature about 2 mV/°C. Power output follows the voltage characteristics, but changes only about 0 3%/°C because of the compensating effect of current which varies directly with temperature.

The most common measure of output of a photovoltaic array is the peak power. This is the maximum power that can be delivered to a matched load under standard conditions of 100 mW/cm^2 solar intensity at 25°C ± 3°C. A properly designed solar module or array will generate the system voltage at relatively low light intensity (10 mW/cm^2) and then the current output

will increase proportionally with light intensity. Also, a solar panel must produce an appropriate voltage and survive in an environment that has rain, snow, hail, high winds, dust, and bird droppings.

Energy Storage System

Since the periods when power is required do not usually coincide exactly with the times when the sun is shining, some form of energy storage is required. This storage also has to provide for periods of low sunlight in poor weather and in similar below-average sunshine conditions. The total energy received from the sun at a location is fairly constant and predictable year to year (Table 2) [9]. Because of this, a solar array can be designed with sufficient precision to meet the overall load, with the storage system smoothing the output to that required (Table 3). It stores the surplus energy generated on sunny days to drive the load at night and in poor weather, as well as making up any deficit that may occur in less sunny months [8]. Batteries typically used are of the lead-acid type having sulfuric acid electrolyte and either pure lead plates or lead-calcium plates. These batteries offer a low self-discharge rate (1% month), a high charge efficiency (95% to 98%), low maintenance (yearly or biannual checks), relatively long life expectancy (10 years), plus they are available with large ampere hour capacities [4].

Battery performance has limits, however. Repeated cycles between charge and discharge can cause sulfation -- growth of lead sulfate crystals on the bottom plates. Repeated deep cycling also causes stress fatigue. Both phenomena shorten battery life. Both can be prevented, in part, by adding more capacity so that the depth of charge never gets below a certain percentage, even in winter (Figure 5). Batteries will last longer and work better if protected from extremes of heat and cold, especially cold. The batteries should be insulated, if possible, or installed below ground level to take advantage of the earth's thermal inertia. Otherwise, more capacity will be needed to reduce the effective depth of discharge. If performance down to -40°C is needed, the battery should be oversized by a factor of 2.5 (refer to Section 2). A feature of lead-acid batteries is that, as the battery cools down, the charging voltage increases; however, this is offset by the silicon solar cell I-V

curve moving to the right along the voltage scale as temperature decreases [8].

The Blocking Diode

In darkness, when the solar array is not generating, the cells are simply a string of diodes which would be forward-biased by the battery. A blocking diode is therefore used to prevent the battery discharging back through the array at night [8]. The forward voltage drop of the diode is then taken into account when choosing the number of series-connected solar cells. Special diodes with extremely low forward voltage drops are used to provide maximum charging voltage to the batteries. They are called Schottky barrier diodes, and typically drop 0.4 V [6].

The Voltage Regulator

A charging regulator is essential to prevent premature failure of batteries on all but the smallest systems, where it may cost less to add massive extra battery capacity. The best regulators for solar power supplies are solid state electronic regulators that deliver full panel output to the batteries until they are fully charged and then shunt all further panel current through circuits that bypass the batteries [6].

Whenever the ampere hour output of a solar generator is more than about 5% of the ampere hour rating of the storage batteries that are used with it, it is recommended that some form of charge control be employed [5]. Otherwise, the batteries may be overcharged. At best, this may mean that the electrolyte will evaporate, requiring refilling; at worst, it may damage the batteries.

It may not be necessary to use a regulator if the solar cell output is fairly constant and close to the load consumption, or if the lost electrolyte can be replaced in summer. Otherwise, a regulator is recommended, and it must always be fitted if the solar array produces 30% excess energy over the year (Table 3) [8].

Monitor Control Unit

In some solar powered applications, such as cathodic protection, it is necessary to include a voltage monitor control unit. This solid state device (schematic diagram, Figure 6) draws its energy from the batteries.

Its function is to provide and maintain a constant "instant-off" polarized potential on the bridge deck of between -0.80 V and -1.25 V. It accomplishes this by continuously comparing the bridge reference electrode with a "set" potential. This "set" potential is adjustable through a 500 Ω 10 turn potentiometer and is usually set 250 mV more positive than the zinc sulphate reference cell. When the reference electrode indicates that the bridge potential is too high (reference electrode potential equals "set" potential), the monitor control unit shuts off any further power to the anodes. The bridge and reference electrode potential will then decay. When the potential difference between "set" and reference electrode fall out of a certain range, the comparator again turns on the power to the anodes. This has the effect of maintaining a narrow potential band on the bridge, as is recommended for cathodic protection of bridge decks.

The control monitor unit has three different output potential taps. Therefore, a constant output potential of 2.2, 2.9 or 3.6 V can be selected simply by choosing the correct tap. The control monitor unit can thus be used on large or small installations where power requirements differ.

In order for the control monitor unit to work properly, a special "remote" non current-carrying ground was required. This special ground eliminated any voltage (IR) drop in the structure line caused by current flow. It was used in conjunction with the reference electrode. With this special ground, a true reference electrode potential can be determined.

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Table 1/ System Performance With Solar Energy

Date	Anode Potential (V) on	Anode Potential (V) off	Anode Current (A)	Solar Array Output (A)
Oct. 28/81	3.9	1.6	0.42	7.9
Nov. 9/81	3.0	1.6	0.36	7.4
Dec. 17/81	2.1	1.2	0.32	1 3
Jan. 13/82	1.6	1.0	0.24	1.0
Feb. 5/82	2.7	1.8	0.13	4.3
Mar. 18/82	1 0	0.8	0.24	1.0
Jun. 8/82	2.1	1.3	0.99	6.0
Jul. 2/82	2.3	1.3	0.90	5.5
Sept. 5/82	2.6	1.5	0.45	4.5

Table 2/ Climatic Data

Scarborough Latitude 43.72 N	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Avg. Temperature (F)	22.0	21.8	31.7	42.3	52.4	63.5	68.6	67.0	60.7	50.8	39.6	27.1
Avg. Degree-Day (F-Day)	1233	1119	1013	615	298	61	7	18	151	439	759	1110
Solar Radiation (Langleys/Month)												
Surface Inclination 30 Deg.	5681	7568	11290	12672	14927	16062	16343	15555	12639	9227	4733	4335
Surface Inclination 45 Deg.	6308	8077	11452	12141	13765	14547	15356	14629	12523	9691	5182	4876
Surface Inclination 60 Deg.	6598	8167	11047	11065	12064	12512	13296	13071	11793	9654	5361	5152
Surface Inclination 90 Deg.	6115	7095	8683	7613	7597	7561	8129	8553	8728	8117	4879	4856

[From Ref. 9, Turn on the Sun, Ministry of Energy, Ontario, Canada 1977.]

Table 3/ System Energy Balance

	A	B	C	D	E
Month	Battery Storage (Ah)	Input from Array (Ah)	Output of Load + 25% (Ah)	Energy at End of Month (Ah)	Excess Energy $\frac{B - C}{A}$ %
June	1025	1742	900	1025	82%
July	1037	1850	930	1037	89%
Aug.	1032	1819	930	1032	86%
Sept.	1018	1642	900	1018	73%
Oct.	995	1344	930	995	42%
Nov.	969	746	900	815	- 16%
Dec	815	717	930	602	- 26%
Jan	602	918	930	590	- 2%
Feb.	590	1137	840	887	50%
Mar.	887	1538	930	951	69%
Apr.	974	1540	900	974	65%
May	997	1679	930	997	75%
					Avg. 49%

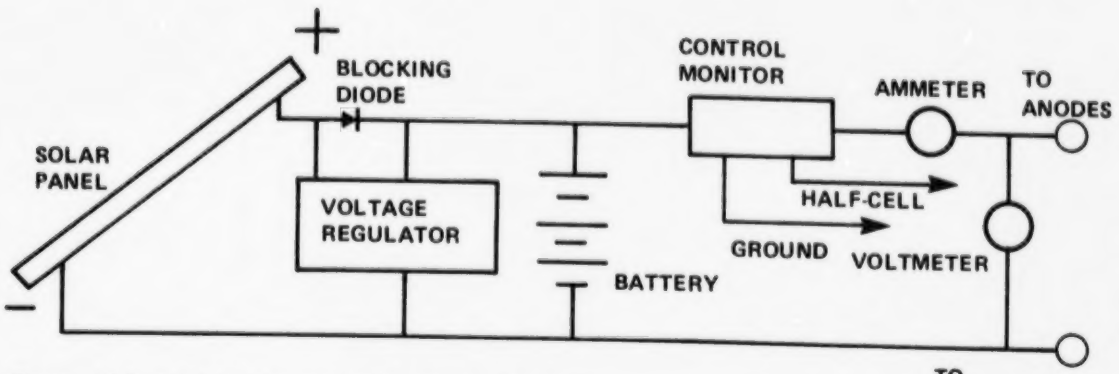

Figure 1/ Simplified Diagram, Solar Power Supply

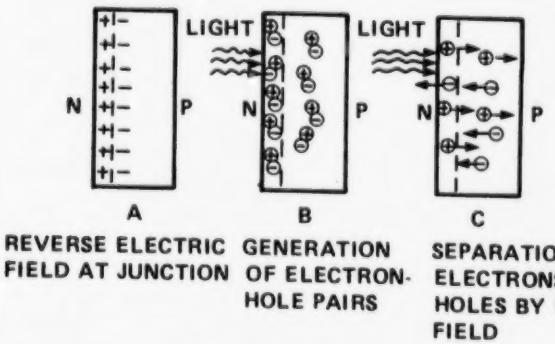

Figure 2/ Silicon Solar Cell, Photovoltaic Effect [From Ref. 4]

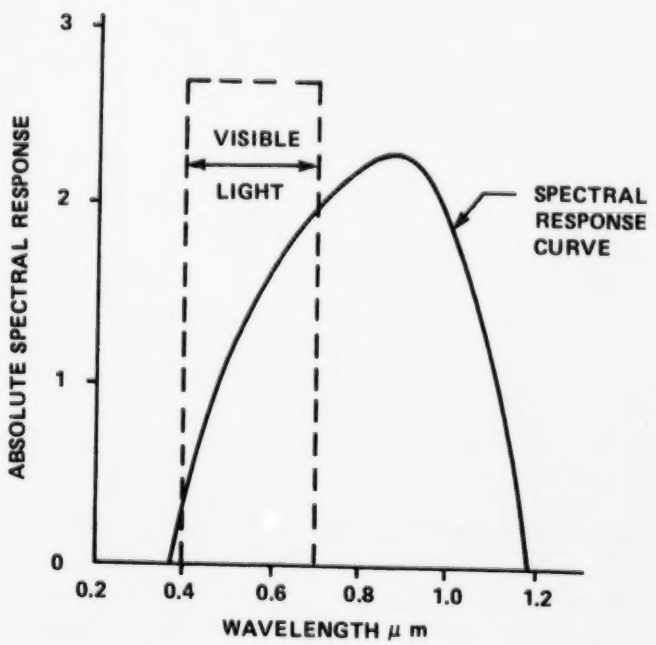

Figure 3/ Typical Solar Cell Spectral Response
[From Ref. 4]

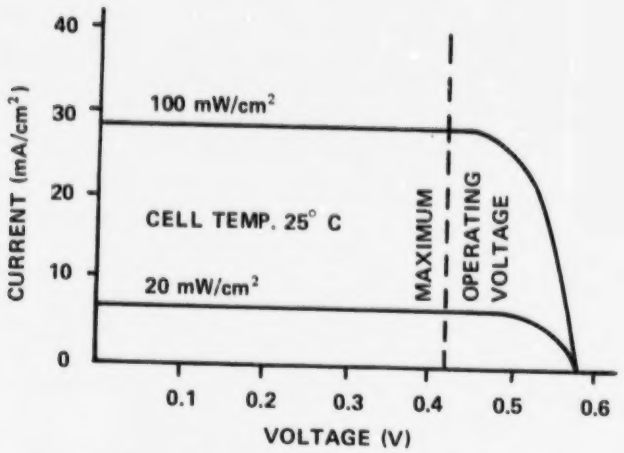

Figure 4/ IV Curves at Various Sunlight Intensities [From Ref. 4]

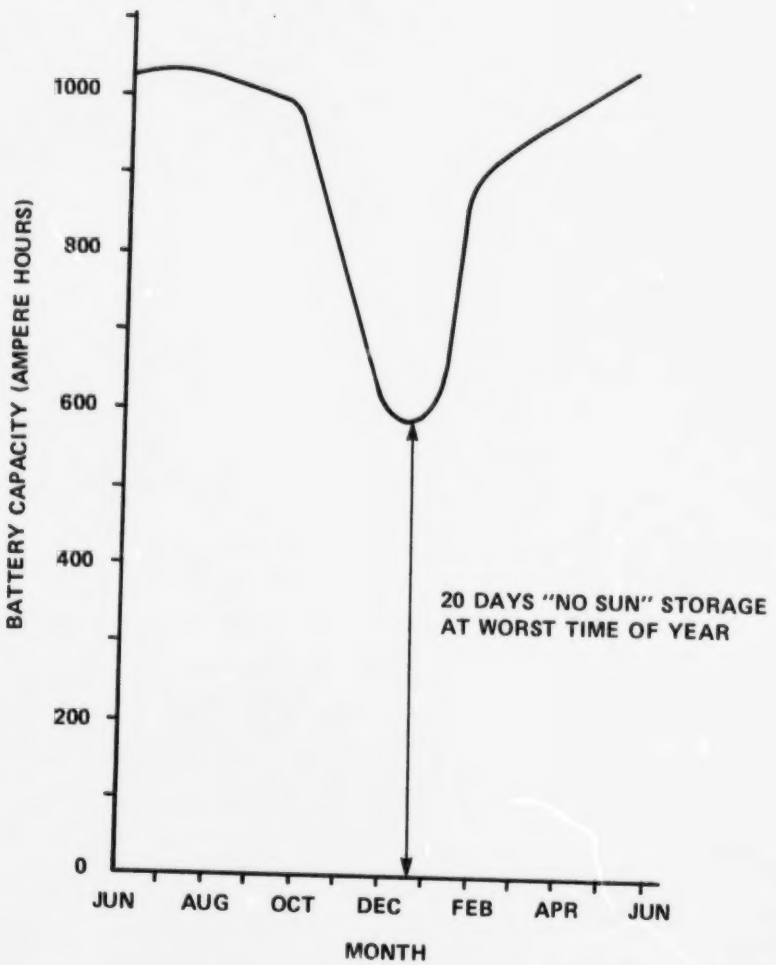

Figure 5/ State of Battery Charge

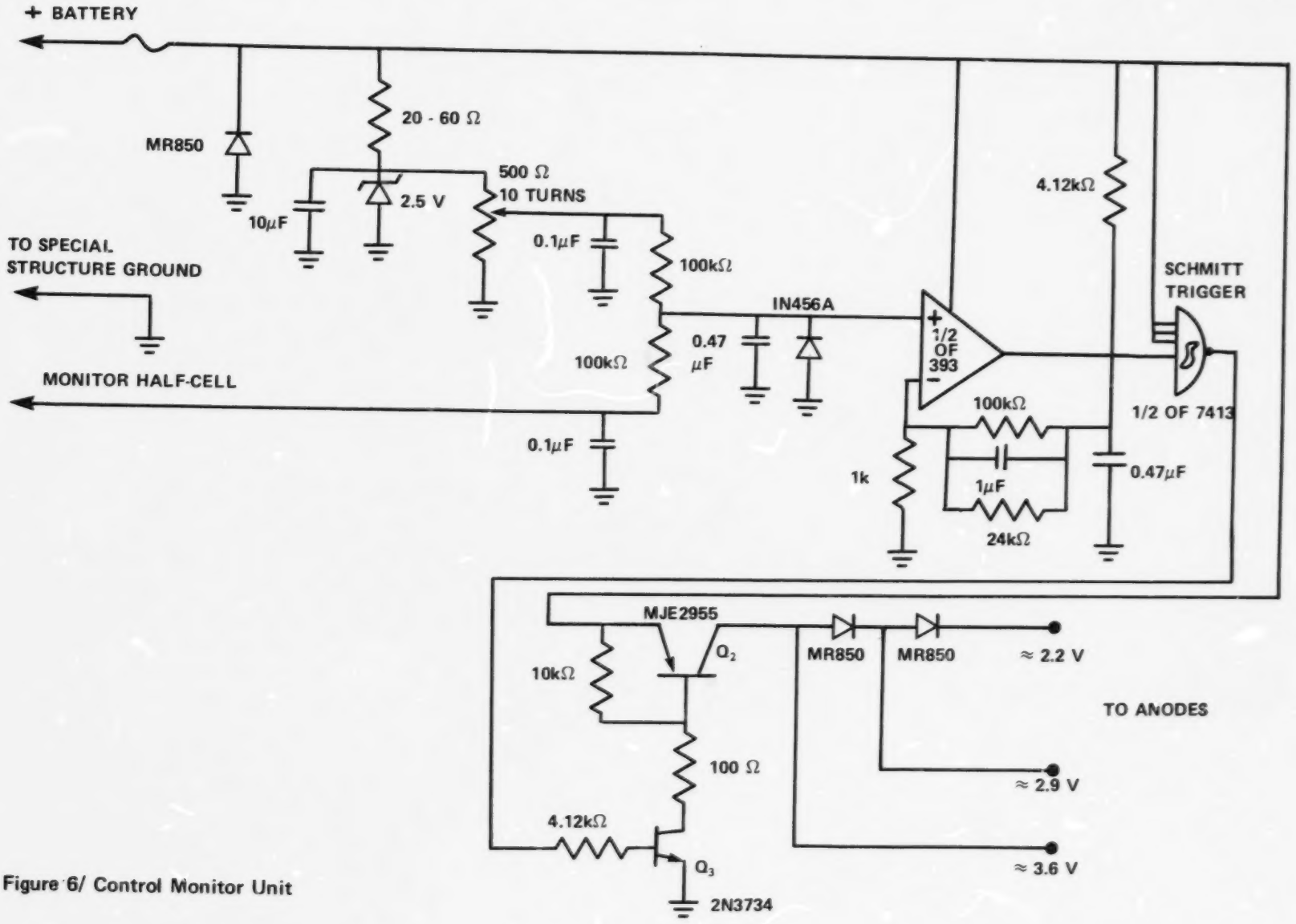

Figure 6/ Control Monitor Unit